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Physical properties of solid biomass

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ABSTRACT

The international biomass market is growing, and is expected to be a large-scale trading market in the long term future. The demand within the European Union, however, cannot be met by local supply. Therefore, a large-scale biomass bulk terminal for both solid and liquid biomass and liquid biofuels is required to accommodate the biomass flows.

The capacity for the large-scale biomass bulk terminal is set at a maximum of 40 million tons per annum, with the estimated share of solid biomass of 40–50 percent. Although some of the issues or concerns (e. g. particle breakage that leads to downstream segregation problems) with regard to storage and handling of biomass can be addressed with the knowledge gained from existing dry bulk terminals, little information is available from the perspective of biomass. Therefore, experiments have been done to determine physical properties of some biomass materials. They are required to allow the design of suitable equipment (e.g. hopper) and handle biomass materials properly, i.e. the materials are handled based on first in first out stock rotation within storage vessel and/or ground storage scheme. Failure to achieve this goal will lead to the risk of negative effects and incidents such as material degradation (due to e.g. fermentation, biological reactions), self-heating (due to exothermic reaction), health hazard, and explosion.

The objective of this paper is to present various decisive physical material properties of three types of solid biomass fuels: wood pellets, wood chips and torrefied pellets. The properties studied are physical material properties and the characteristics when the materials interact with the storage and handling equipment. In addition to the results, among which particle size distribution and angle of internal friction, the experimental setup as well as the relevant standards (e.g. ASTM and CEN) will be described.

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1. Introduction

As one of the significant renewable energy sources, biomass materials and refined/derived biomass products have been traded internationally. The international biomass market is currently still growing, and is expected to be a large-scale trading market in the long term future. To fulfill EU directive targets in the long term future, significant amounts of materials will be imported in to the EU. Hence, a large-scale biomass terminal situated in West Europe is required to accommodate the import biomass flows, and the terminal also fits in the picture of large-scale biomass trades and long distance biomass supply chain [1].

The maximum throughput for such a large-scale biomass bulk terminal is set at 40 million tons per annum, including both solid and liquid biomass [1]; this implies that substantial storage facilities, handling systems, and space are required. Storage and handling are two of the essential functions of a seaport terminal, since it provides for uncoupling the incoming and outgoing material flows to overcome potential

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supply inconsistencies (e.g. seasonal influences). The challenge for the terminal is that in addition to the large material quantities which will flow through, there will be several types of biomass handled on the terminal, each with its unique material characteristics. Although many of the problems (e.g. tendency to bridge, segregation, dust generation) or concerns with regard to storage and handling of biomass can be learned from dry and liquid bulk material handling, currently little work is found from this perspective. Selection and design of biomass handling and storage equipment strongly depends on the physical material properties of biomass materials, therefore, the material properties of biomass need to be determined.

The objective of this paper is to present various significant physical material properties of solid biomass fuels through a range of tests. Firstly, three types of solid biomass fuels that might be handled potentially at the biomass terminal were chosen. Experiments were set up and several test standards (e.g. CEN standards) and biomass material standards (e.g. Austrian and German wood pellet standards) were used as references. These tests investigated a wide range of aspects, including the important physical material properties (e.g. particle size, angle of internal friction), and the characteristics when the materials interact with the storage and handling equipment (e.g. adhesion, wall friction, impact breakage). Finally, the test results of physical properties of these three materials are presented and discussed.

2. Materials and methods

Several experiments were performed in order to obtain the decisive physical properties that are crucial for handling and storage of solid biomass. The materials used here were wood pellets, wood chips, and torrefied pellets; the description of these materials will be given in section 2.1. Section 2.2 shows the measurement procedures for each test, together with the test standards that were complied with.

2.1. Test materials

Seven test materials were selected to perform the tests. The test materials used are obtained from a major solid biomass user, namely a co-firing power plants, for wood pellets and wood chips. Torrefied pellets are also included in the test materials, based on the expectation that in the future, the torrefaction technique will play a key role, and thus the torrefied pellets will be crucial as well [2]. Information of the raw materials will be given in the following sections. All these test materials were representative of the feedstock used by the power plant throughout the years.

Table 1 – Initial material information of wood pellets [3].

Origin	Moisture content (%)	Diameter (mm)
Canada	< 10	6
Canada	< 10	8
Canada	< 10	12

Table 2 – Initial material information of wood chips [3].

Origin	Age (month)	Moisture content (%)	Dimension (length in mm)
The Netherlands	6–9	35–45	0–20
The Netherlands	6–9	35–45	0–40
The Netherlands	6–9	35–45	0–100

The test materials were stored in 200 L drums sealed off by lids. The drums were mainly stored indoors.

2.1.1. *Wood pellets*

The wood pellets used in the experiments consisted of three different diameters: 6 mm, 8 mm, and 12 mm, and varied in length. The pellets originated and were imported from Canada, and are used as feed in co-firing power plants in the Netherlands [3]. Table 1 shows the given specification of the wood pellets as received.

2.1.2. *Wood chips*

Wood chips were chosen as a second material, the reason for this is due to the fact that power plants also use them often for daily practices (e.g. as feedstock for gasification). The experiments made use of fresh wood chips from Dutch forests with three different dimensions, also the same as the feedstock fed into power plants. Table 2 displays the initial information about the wood chips as received.

After stored in the drums for 3 months, phenomena of partially rotten wood chips were observed. This is due to the high moisture content of the wood chips together with the presence of oxygen (oxygen goes into the drums when the lid was open in order to get sample materials). Hence, the wood chips became more brittle.

2.1.3. *Torrefied pellets*

Torrefied pellets (referred as BO_2 pellets in this paper[2]) are the new products that result from combining the torrefaction and pelletization techniques, and they are still in the pilot stage of production.

Above sections show that the test materials were: wood pellets (6, 8, 12 mm), wood chips (0–20, 0–40, 0–100 mm), and the torrefied pellets. Hence, there were seven test materials in total.

2.2. *Methods*

Currently there are many test standards available for bulk solid material handling [i.e. [5,6]]. Although some standards have been built by individual countries (e.g. Austria, Sweden, Germany), most of the test standards for handling solid biomass fuels in EU level are still in the developing phases [7]. Some characteristics of solid biomass fuels make it difficult or impossible to comply with existing bulk solid test standards. For instance, the particle size can be too large to use the traditional test methods (e.g. the diameters of wood pellets are too big for using Jenike shear cell), or the heterogeneous

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[2] Registered name by Energy Research Centre of the Netherlands (ECN).

Table 3 – Initial material information of torrefied pellets [4].

Origin	Date of torrefaction	Date of pelletization	Density (kg/m^3)	Moisture content (%)	Dimension (diameter in mm)	Remark
The Netherlands	March 12, 2009	June 4, 2009	670	2–3	6	Feedstock: poplar chips

nature of solid biomass fuels makes it difficult for conventional tests (e.g. the length of wood chips is oversized for using Jenike shear cell) [5].

Nevertheless, the principles of various commonly used experiments can still be used as the background knowledge for testing solid biomass fuels. Thus, the sections below will describe the procedures for each test, with the use of national test standards (e.g. German standard, Austrian standard) and other bulk solids test standards as references [5,6,8,9,13,18,19].

In addition, all the experiments were performed based on statistical accuracy of 95% confidence interval.

2.2.1. *Density test*

Two types of density tests were performed to determine the bulk density and particle density of the test materials. Bulk density tests were carried out for all seven materials, while particle density tests were done for pelletized materials only.

2.2.1.1. *Particle density*. A random selection of 16 particles was done for the pelletized materials (i.e. torrefied pellets 6 mm, wood pellets 12 mm, wood pellets 8 mm, wood pellets 6 mm), according to ÖNORM M 7135 [8]. The length and the weight of each particle were measured, and the given particle diameters were validated and used. The average value of particle density was calculated per material; with this the void ratio of pelletized test materials can be derived.

2.2.1.2. *Bulk density*. The weight and the volume of the test samples were measured in order to be able to calculate the bulk density. The weight was measured by a laboratory balance; the volume was determined by two types of measuring containers: a steel pan and a 1 L steel can (due to large particles of wood chips 0–100 mm; a container of 5.35 L was used in that case). A measurement series of ten times per test material was performed and the average value of bulk density was calculated for each material.

2.2.2. *Oven dry test*

The actual moisture content of the test materials were determined by oven dry tests. The tests were performed according to the CEN/TC 335 biomass standard. The technical specification followed was "Solid biofuels – methods for determination of moisture content – oven dry method – part 1: total moisture – reference method" [9].

Ten samples of 300–500 g were weighed before and after being dried in the oven, all samples were dried to constant weights within 24 h. The ovens used in the tests were the Heraeus ovens (Heraeus M110 and Heraeus K750), controlled at 105 ± 2 °C.

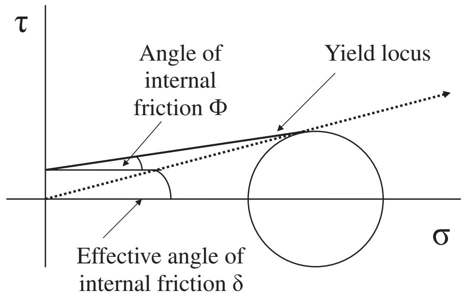
τ
Angle of internal friction Φ
Yield locus
σ
Effective angle of internal friction δ

Fig. 1 – Effective angle of internal friction.

2.2.3. *Particle size distribution test*

The particle size distribution is an important physical property of the solid biomass materials because together with the moisture content, they influence the flow properties of the material in transport and storage systems. Furthermore, the handling (e.g. tendency to bridge) and combustion characteristics will be affected as well [10–12]. The understanding of particle size distribution will also help to deploy suitable handling and storage equipment.

For all the test materials, 10 samples of 1 L (around 280–650 g) of materials were taken for conducting the experiment. For pelletized test materials, sieving with 9 different sizes of sieves (ranging from 6.3 to 50 mm) was conducted. For wood chips, the lengths of the particles were determined by using horizontal screening method, according to CEN/TC 335 test standard [13]. A three-dimensional shaker (Haver & Boekler EML 450) with 400 mm diameter screens was used, and each wood chip sample was shaken for 10 min with amplitude of 1 mm. The results were classified into several groups, and the weight of each group was determined.

2.2.4. *Large-scale annular shear test*

The basic concept of a shear test is to apply a certain normal force on top of a test material while the material is

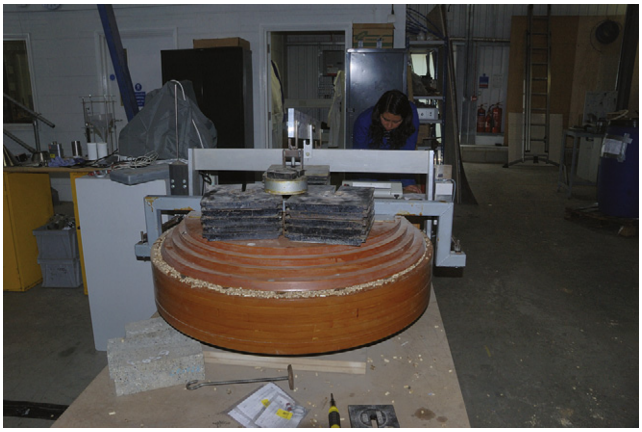

Fig. 2 – Large-scale annular shear tester.

Table 4 – Normal load sequence of the large-scale annular shear test.

Sequence	1		2		3	
	kg	kPa	kg	kPa	kg	kPa
Pre-consolidation load	52	1.0	104	1.8	208	3.4
Lowest normal load	17	0.4	34	0.7	68	1.2
Medium normal load	34	0.7	68	1.2	139	2.3
Highest normal load	52	1.0	104	1.8	208	3.4

horizontally sheared. If the procedure is repeated several times with different normal forces, then a yield locus graph can be obtained [10,14]. Important parameters with regard to design of equipment can be derived from shear test, such as effective angle of internal friction (δ). Fig. 1 illustrates the angle of internal friction from the normal stress (σ), shear stress (τ) diagram.

The shear tests were conducted by a large-scale annular shear tester, as shown by Fig. 2. A chart recorder was used to take down the readings, and a sequence of normal loads that reflects the practical situation was applied on top of the lid of the shear tester, as expressed by Table 4. The test procedures were the same as in the standard for Jenike shear test [5].

2.2.5. *Linear wall friction test*

The definition of the wall friction angle Φ_{wall} can be expressed by Fig. 3 and equation (1).

$$\Phi_{\text{wall}} = \tan^{-1}(\tau_w/\sigma_w) \quad (1)$$

Four wall material samples were used together with all seven test materials for the wall friction tests: concrete, mild steel, stainless steel, and UHMW-PE (Tivar 88). Test materials were put into a ring with 27.7 cm in inside diameter, and 2.5 cm in height; a 1.295 kg lid was put on top of the test materials. The wall material samples were placed under the ring, as shown by Fig. 4.

The normal loads were applied on top of the lid, and a loading stem that was electrically driven with a rate of 0.152 cm/s provided the shearing action. A minimum of five shear tests were performed for each yield locus, and the shear force was recorded by a chart recorder (accuracy: 0.5 mm). Table 5 presents the normal stress levels applied in this experiment.

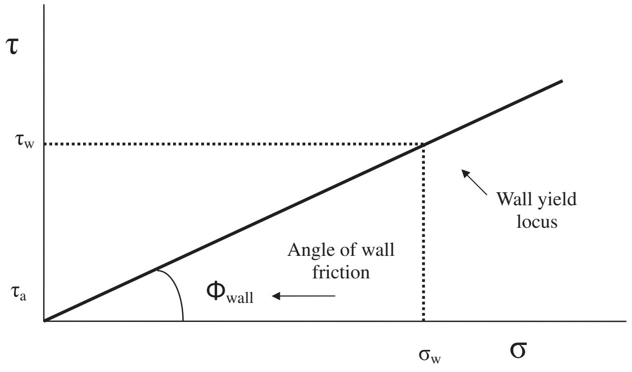

Fig. 3 – Wall yield locus.

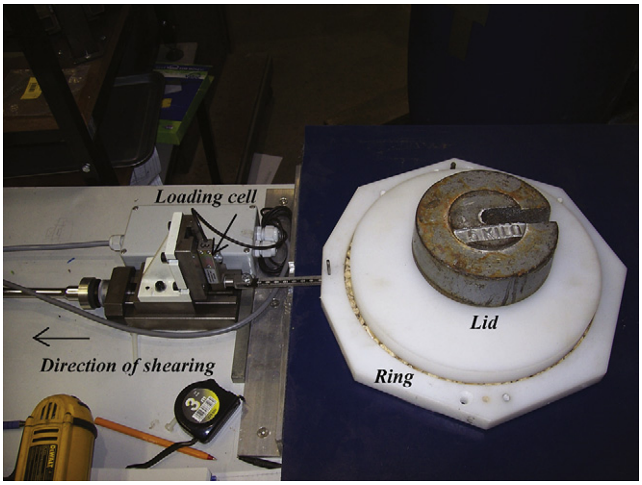

Fig. 4 – Linear wall friction test apparatus (D = 27.7 cm, h = 2.5 cm, v = 0.152 cm/s).

2.2.6. *Angle of repose test*

The tests conducted here were to measure the loose-based angles of repose [15]. Fig. 5 shows that equipment used including a steel cone shaped container (outlet diameter is 10.6 cm) functioned as a funnel for the test materials to drop. The test materials, fixed with a volume of 20 L, were then dropped on top of a board. The test procedure was:

1. Fill the test materials into the bucket with a volume of 20 L.
2. Fix the cone shape container at a pre-determined dropping height. For wood pellets and torrefied pellets the dropping distance was 23 cm from the outlet of the cone shape container to the board. Due to longer and heterogeneous particle shapes, the dropping height was increased to 30 cm for the wood chips.
3. Put a thin layer of test materials underneath the cone shape container outlet, in order to eliminate the bouncing effect from dropping materials onto the board.
4. Carefully feed the test materials into the cone shape container to let the test materials drop on the surface of the board under the cone shape container, to form a pile.
5. Take a picture once all the testing materials from the bucket were fed. Use the protractor to directly measure the angle of repose at 4 points (Fig. 6).
6. Use ropes and rulers to measure the height and the circumference of the pile [15,16].

Table 5 – Normal loads applied for the linear wall friction test.

Normal load (kg)	Normal stress (kPa)
0.5	0.1
2.5	0.4
5.5	0.9
10.5	1.7
15.5	2.5
20.5	3.4
25.5	4.2

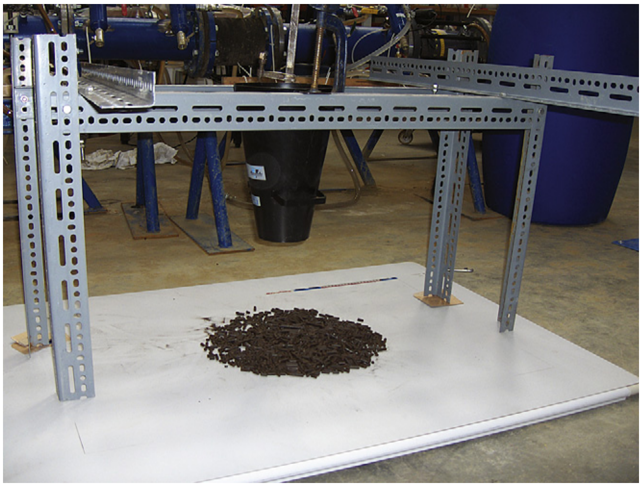

Fig. 5 – Angle of repose apparatus.

2.2.7. *Attrition test*

Attrition tests were carried out in order to test the vulnerability of pelletized materials (torrefied pellets 6 mm, wood pellets 12 mm, 8 mm, and 6 mm), especially for impacts between the materials and equipment (e.g. wood pellets falling on belt conveyor during transfer). Wood chips were not tested with this experiment, due to the ductility nature of wood fibers.

An attrition test apparatus was used (see Fig. 7), with two different disk rotating speeds were used to observe the breakage phenomena of the pelletized materials: 240 rpm (the impact velocity is 6.5 m/s) and 900 rpm (the impact velocity is 24.3 m/s). The angle of the steel plates lined up inside the attrition test apparatus was 45°. Sieves of 14 mm, 6.3 mm, and 2.8 mm were used to exam the percentage of fines created as the results of the tests.

The experimental procedure was as followed:

1. Take a sample of 1.2–2.4 L (depends on the particle diameter) from the test materials. Weigh the test sample and take a picture. Feed the material into the attrition test apparatus, the apparatus rotated with pre-determined speed.

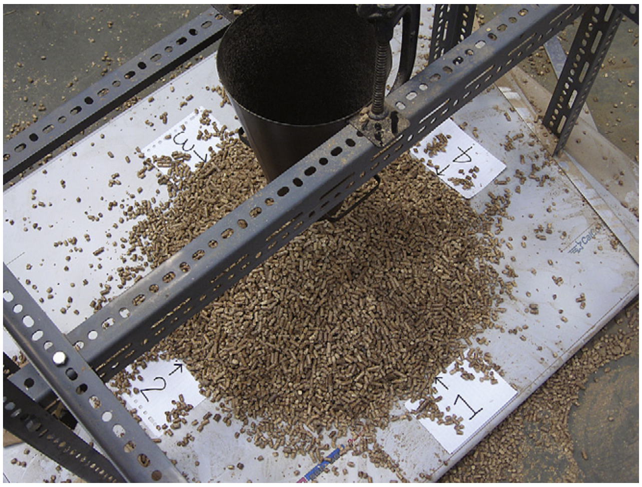

Fig. 6 – Direct measurement points of the angle of repose test.

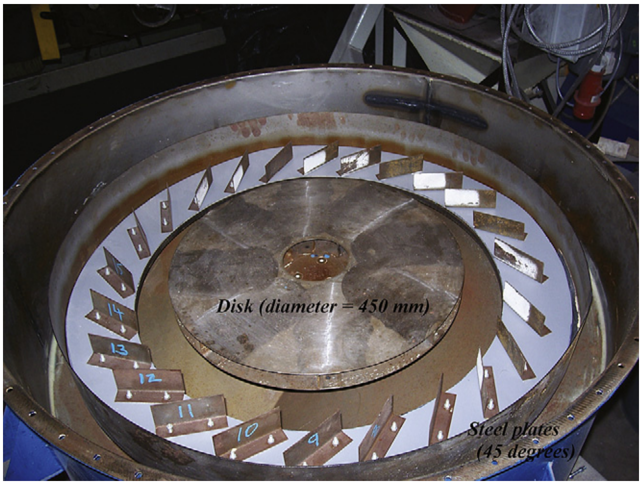

Fig. 7 – Attrition test apparatus.

2. Collect the test sample after the test is finished. Weigh the test sample, and then manually sieve the test sample through 14 mm, 6.3 mm, and 2.8 mm sieves.
3. Weigh the sample materials left on the bottom sieve pan and the sample materials left on the sieve pans. Take a picture of the test sample as the state after the test.
4. The before and after state pictures are compared, and the numbers of pellets with their length on the pictures are measured.

3. Results and discussions

The results from the experiments are presented in this chapter, in terms of maximum, minimum, and average values; in addition, the standard deviation of the results will be shown as well. The only exception is the attrition test results, which is presented as a relative ranking outcome.

3.1. *Density*

3.1.1. *Particle density*

The results of particle density for pelletized materials are shown in Table 6. According to Austrian wood pellet standard ÖNORM M 7135 [8,17], German pellet standard DIN 51731 and DIN plus [18–20], the guiding value is 1120 kg/m^3 Table 6

Table 6 – Results of particle density for pelletized test materials.

Material	Max (kg/m^3)	Min (kg/m^3)	Average (kg/m^3)	Standard deviation (kg/m^3)
BO$_2$ 6 mm	1361	1280	1325	26
Wood pellets 6 mm	1901	1577	1764	104
Wood pellets 8 mm	1901	1471	1687	124
Wood pellets 12 mm	1296	1103	1199	48

Table 7 – Average bulk density of the test materials.

Material	Max (kg/m^3)	Min (kg/m^3)	Average (kg/m^3)	Standard deviation (kg/m^3)	Void ratio (%)
BO_2 6 mm	668	610	642	20	52
Wood pellets 6 mm	629	583	609	11	66
Wood pellets 8 mm	649	588	621	16	63
Wood pellets 12 mm	528	498	510	9	58
Wood chip 0–20 mm	250	209	228	10	N/A
Wood chips 0–40 mm	273	230	256	14	N/A
Wood chips 0–100 mm	261	249	256	3	N/A

Table 8 – Moisture content of the test materials.

Material	Max (%)	Min (%)	Average (%)	Standard deviation (%)
BO_2 6 mm	4.1	3.9	4.0	0.1
Wood pellets 6 mm	8.2	8.0	8.1	0.1
Wood pellets 8 mm	8.2	8.1	8.2	0.0
Wood pellets 12 mm	11.2	10.5	11.0	0.2
Wood chips 0–20 mm	50.9	48.3	49.3	0.8
Wood chips 0–40 mm	42.3	40.6	41.7	0.5
Wood chips 0–100 mm	49.7	47.1	48.6	0.9

indicates that the average value of the pelletized test materials exceed the value stated in these standards. The particle density affects the bulk density of solid biomass materials and their combustion behavior, since dense particles show a longer burnout time [21].

A major difference occurs between wood pellets of 12 mm and 6 mm, this may be caused by different types of saw dust that were used for producing these wood pellets.

3.1.2. *Bulk density*

The bulk density tests were conducted using two different vessels: a steel pan and a 1 L steel can. Table 7 shows the bulk density value of the test materials, the values presented here are used for the rest of the experiments if bulk density is required. In addition, the void ratios of the pelletized test materials are included.

Judging from the results, the pelletized materials have higher bulk densities than wood chips. For wood pellets, the bulk density varies in between 498 and 649 kg/m^3, while literature [22–24] points out the value is between 600 and 750 kg/m^3 and that wood pellet producers often state that the design value of bulk density is 650 kg/m^3 [21]. Similar to the results from particle density test, there is also a significant difference between wood pellets of 12 mm and 6 mm, the reason for this might again be due to different wood species used as feedstock to produce these pellets.

As for wood chips, the measured value is between 209 and 273 kg/m^3, values from literature [23–25] are between 150 and 400 kg/m^3. It is obvious that the bulk density for wood pellets and wood chips fall into the lower end of the range stated in the literature. This indicates a negative effect on the transportation costs and subsequently on the storage and transport capacity (in terms of volume) for these materials. The moisture content may affect the results of bulk density test, especially for wood chips. If the moisture content of wood chips is lower, the bulk density is expected to be lower, yet still within the range stated in the literature.

Torrefied pellets hold the highest bulk density among all the test materials from both ways of measurement. The measured bulk density is between 610 and 668 kg/m^3; it suggests that torrefied pellets do have logistical advantage compared to wood chips, due to more condensed form.

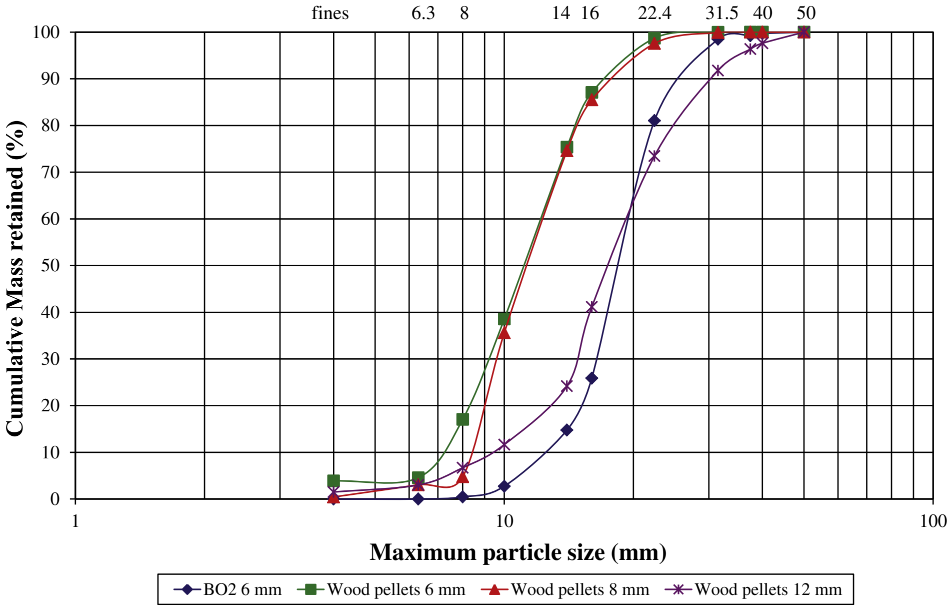

Fig. 8 – Cumulative particle size distribution of pelletized test materials.

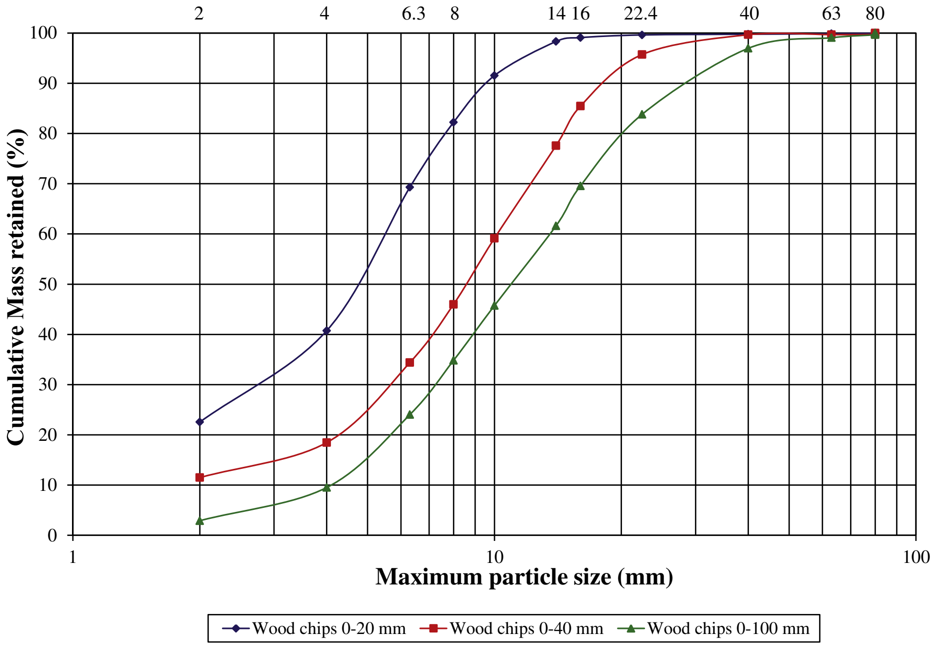

Fig. 9 – Cumulative particle size distribution of wood chips.

3.2. *Moisture content*

The moisture content of solid biomass influences the net calorific value and the combustion efficiency. The method for the determination of moisture content is to calculate the differences in weight of the samples before they were put into oven and after, note that the method applied here is moisture content on wet basis. The guiding value from ÖNORM M7135 and DIN plus is below 10%, while DIN 51731 states the moisture content should be below 12% [8,17,18,20]. The results of the oven dry test are presented in Table 8; except 12 mm wood pellets all pelletized test materials have moisture content below 10%: between 3.9 and 8.2%. Torrefied pellets show significant low water content among all the test materials, while wood chips have quite high moisture content, varies between 40.6 and 50.9%.

3.3. *Particle size distribution*

The results of the particle size distribution of the test materials are divided into two groups: pelletized test materials and wood chips. For all the pelletized test materials, the diameters of the particles fit in with the initially given material information, as stated in Table 1 and Table 3. Thus, the measurements are focused on the lengths of the particles. The cumulative particle length distribution of the pelletized test materials is shown by Fig. 8, with the sieve sizes used in the experiment (note: “fines” are defined as the small fractions, not complete pellets). As for wood chips, the measured dimension of the particles is also the maximum particle dimension. The results are illustrated by Fig. 9, also with the sieve sizes used in the tests.

The median value (i.e. cumulative percentage is 50%) in terms of mass can be obtained from Figs. 8 and 9; this gives an indication of particle size of the test materials, which is important for comparing to characteristic size of handling equipment.

3.4. *Angle of internal friction and effective angle of internal friction*

Section 2.2.4 and Fig. 1 explain the concepts and definition of angle of internal friction and effective angle of internal friction, derived from shear test. Angle of internal friction can be

Table 9 – Angle of internal friction.

Material	Max (°)	Min (°)	Average (°)
BO_2 6 mm	50	41	46
Wood pellets 6 mm	38	35	37
Wood pellets 8 mm	43	38	41
Wood pellets 12 mm	37	33	35
Wood chips 0–20 mm	46	44	45
Wood chips 0–40 mm	49	44	47
Wood chips 0–100 mm	48	46	47

Table 10 – Effective angle of internal friction.

Material	Max (°)	Min (°)	Average (°)
BO_2 6 mm	56	44	49
Wood pellets 6 mm	42	39	40
Wood pellets 8 mm	45	41	43
Wood pellets 12 mm	42	40	41
Wood chips 0–20 mm	54	51	53
Wood chips 0–40 mm	53	50	51
Wood chips 0–100 mm	51	44	48

Table 11 – Wall friction angles - PE (Tivar 88).

Material	PE (Tivar 88)			
	Max wall friction angle (°)	Min wall friction angle (°)	Average wall friction angle (°)	Standard deviation (°)
BO_2 6 mm	12	12	12	0
Wood pellets 6 mm	15	11	13	2
Wood pellets 8 mm	13	10	11	1
Wood pellets 12 mm	13	9	11	1
Wood chips 0–20 mm	28	19	22	3
Wood chips 0–40 mm	27	18	22	3
Wood chips 0–100 mm	20	14	17	2

Table 12 – Wall friction angles - Concrete.

Material	Concrete			
	Max wall friction angle (°)	Min wall friction angle (°)	Average wall friction angle (°)	Standard deviation (°)
BO_2 6 mm	31	27	29	1
Wood pellets 6 mm	32	30	31	1
Wood pellets 8 mm	35	31	33	1
Wood pellets 12 mm	31	29	30	1
Wood chips 0–20 mm	34	33	33	1
Wood chips 0–40 mm	33	30	31	1
Wood chips 0–100 mm	37	35	35	1

Table 13 – Wall friction angles - Mild Steel.

Material	Mild Steel			
	Max wall friction angle (°)	Min wall friction angle (°)	Average wall friction angle (°)	Standard deviation (°)
BO_2 6 mm	18	15	16	1
Wood pellets 6 mm	20	16	18	2
Wood pellets 8 mm	22	15	18	2
Wood pellets 12 mm	20	17	18	1
Wood chips 0–20 mm	33	28	30	2
Wood chips 0–40 mm	31	25	27	2
Wood chips 0–100 mm	33	29	31	2

Table 14 – Wall friction angles - Stainless Steel.

Material	Stainless Steel			
	Max wall friction angle (°)	Min wall friction angle (°)	Average wall friction angle (°)	Standard deviation (°)
BO_2 6 mm	26	23	25	1
Wood pellets 6 mm	19	18	19	1
Wood pellets 8 mm	21	18	19	1
Wood pellets 12 mm	20	17	18	1
Wood chips 0–20 mm	35	30	31	2
Wood chips 0–40 mm	31	28	29	1
Wood chips 0–100 mm	33	30	31	2

Table 15 – Results of directly measured angle of repose.

Material	Max (°)	Min (°)	Average (°)	Standard deviation (°)
BO_2 6 mm	46	42	43	1
Wood pellets 6 mm	41	39	40	1
Wood pellets 8 mm	40	37	39	1
Wood pellets 12 mm	41	37	38	2
Wood chips 0–20 mm	48	44	46	2
Wood chips 0–40 mm	48	44	46	1
Wood chips 0–100 mm	49	43	46	2

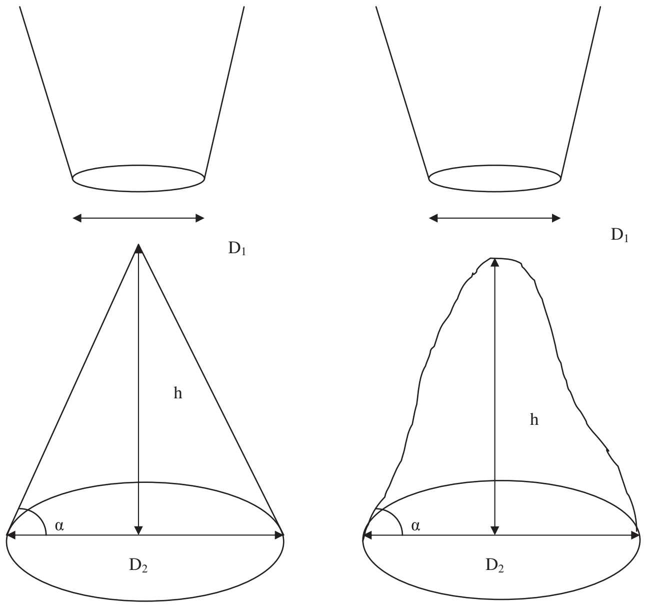

Fig. 10 – Differences in perfect and real cone shape.

calculated as the gradient of yield locus. The effective angle of internal friction can be calculated from the line that passes through the origin, and is tangential to the Mohr's circle from the end of the yield locus.

The angle of internal friction and the effective angles of internal friction resulting from the large-scale annular shear tests are presented in Table 9 and Table 10. Both Table 9 and Table 10 demonstrate that torrefied pellets and wood chips have highest angles, and wood pellets have lowest angles.

3.5. *Wall friction angle*

The wall friction angle is one of the important physical properties, because it gives indication of the situations when solid biomass materials in contact with different kinds of surfaces. From the linear wall friction test, a graph of wall yield locus can be plotted that describes the relation between a normal stress (σ) and the shear stress (τ) needed to move the test materials across a wall material [10]. The details of the wall material samples are as follows: UHMW-PE (Tivar 88) - this is manufactured to a given thickness and not skived from a block. Concrete - this was cut from a block (diamond saw). Mild steel – mill scale (i.e. no polish or sanding undertaken - plate in "as supplied" condition). Stainless steel - this was 304 2B (i.e. cold rolled so that the surface finish is non directional and smooth).

The results of the wall friction angles based on equation (1) are summarized in Tables 11–14. The adhesion between test materials and wall materials is negligible.

The results from all wall friction tests for all test materials show that the lowest wall friction angle for solid biomass materials is from PE, while concrete gives the highest values. These results are as expected due to the observation that the surface roughness of concrete is the coarsest while PE has the smoothest surface. In addition, it was observed during the test that pelletized test materials were rolling, therefore it was a combination of rolling and sliding friction, while for wood chips only sliding friction was noted.

3.6. *Angle of repose*

The angle of repose is one of the primary properties of bulk solids that indicates the flow behaviors of granular materials, such as flow-ability, avalanching, and stratification [15]. The experiment performed allows two way of obtaining the angle of repose, namely direct measurement and calculation of circumferences and heights of the piles (alternative calculation) [15,16].

Four points were used for direct measurements with a protractor, and then the average value out of these four points was calculated. Table 15 shows the average directly measured angle of repose for all seven test materials, together with the maximum and minimum measured value, and the standard deviation.

In an ideal situation, a perfect cone shape pile is the outcome of the test; however, this is highly unrealistic in

Table 16 – Angle of repose results from alternative calculation.

Material	Alternative calculated max (°)	Alternative calculated min (°)	Alternative calculated average (°)	Alternative calculated standard deviation (°)
BO_2 6 mm	39	37	38	1
Wood pellets 6 mm	37	32	35	1
Wood pellets 8 mm	39	35	37	1
Wood pellets 12 mm	36	32	35	1
Wood chips 0–20 mm	47	42	44	2
Wood chips 0–40 mm	47	42	44	1
Wood chips 0–100 mm	50	43	46	2

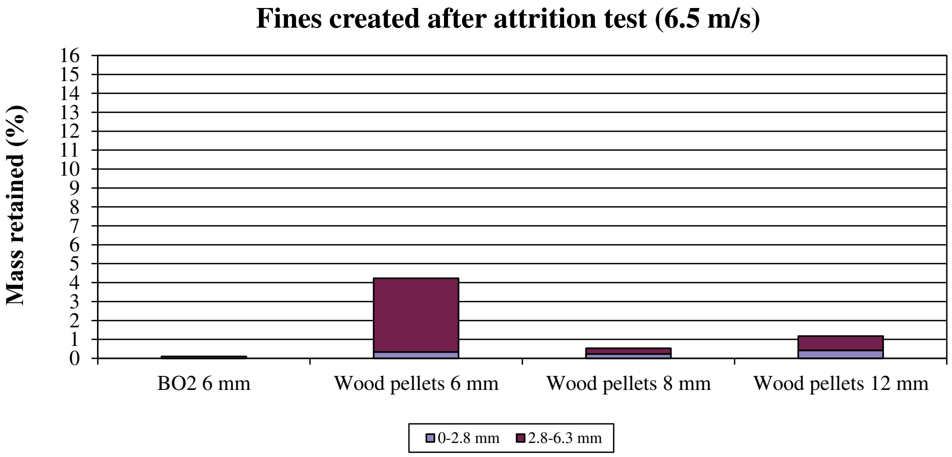

Fig. 11 – Attrition test results – fines percentage (6.5 m/s).

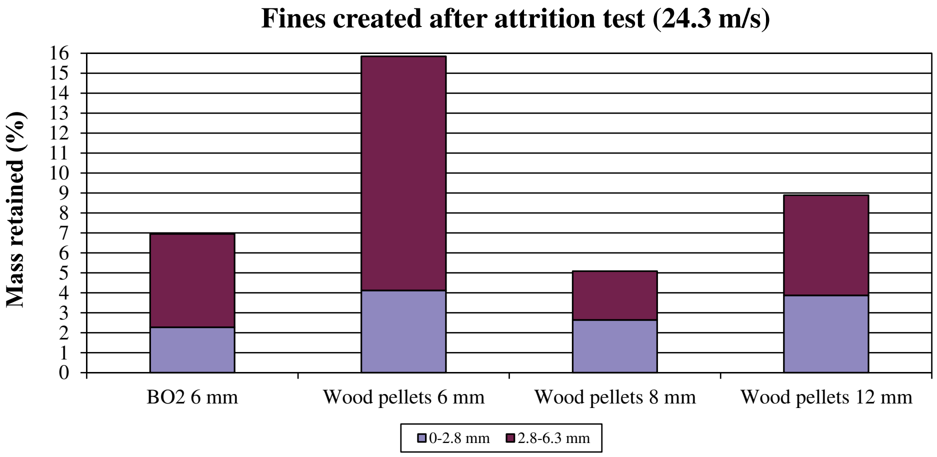

Fig. 12 – Attrition test results – fines percentage (24.3 m/s).

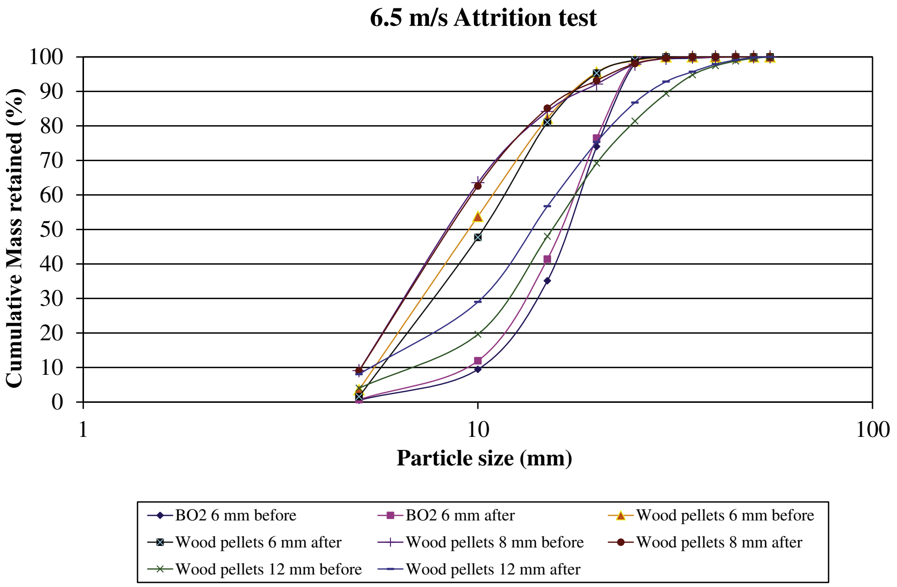

Fig. 13 – Attrition test particle size distribution results (6.5 m/s).

Table 17 – Summary of the experiment results.

Properties	Material	Wood pellets	Wood chips	Torrefied pellets
Physical Characteristics	Particle Density (kg/m^3)	1103–1901	N/A	1280–1361
	Bulk Density (kg/m^3)	498–649	209–273	610–668
	Particle max length (mm)	See Figs. 8 and 9		
	Particle diameter (mm)	6, 8, 12	N/A	5.8
	Moisture Content (%)	8–11	41–51	3.9–4.1
	Angle of internal friction (°)	33–43	44–49	41–50
	Effective angle of internal friction (°)	39–45	44–54	44–56
	Angle of repose (°)	32–41	42–50	37–46
handling equipment in contact with solid biomass materials	Breakage	easy to break	N/A	stronger than wood pellets
	Wall friction angle (°)	9 – 35 PE – Concrete	14–37PE–Concrete	12 – 31 PE – Concrete

N/A: Not applicable.

practice. Assume that the outlet funnel used in the test has a diameter of D_1, the height of the pile is h, the diameter of the pile is D_2, and α represents the angle of repose. Fig. 10. illustrates the difference between a perfect cone shape pile and the pile obtained from experiment in practice.

Thus, an alternative way for the angle of repose is to calculate α from the circumference (C) and the height of the piles. From Fig. 10, the equation to calculate á is:

$$\alpha = \tan^{-1}[h/(D_2 - D_1)/2] \tag{2}$$

D_2 can be derived from the circumference (C):

$$D_2 = C/\pi \tag{3}$$

Thus, the equation becomes:

$$\alpha = \tan^{-1}[2h/(C/\pi - D_1)] \tag{4}$$

Table 16 presents the results of alternative calculation from equation (4):

If Table 15 and Table 16 are compared then the results match with literature [26]. It also shows that the values of directly measured angle of repose are much higher than alternative calculation.

3.7. *Breakage*

Particle breakage and fines generation by abrasion can be assessed through attrition test, the sensitivity of test materials to attrition thus can be compared [10]. The calibration of the attrition test apparatus showed that with the two disc rotating speeds used (240 and 900 rpm), the corresponding particle velocities were around 6.5 and 24.3 m/s. Compared to practical situation, these velocities are rather high, however, the disk rotating speeds were chosen to exam the susceptibility of the pelletized test materials under extreme conditions, and give a relative ranking of the materials.

The outcomes of the attrition test are assessed by measuring the percentage of fines of each pelletized test material after the experiments. The definition of "fines" is the fractions of after state test materials that passed 6.3 mm sieve. The outcomes of the attrition test in terms of percentage of fines are illustrated by Fig. 11 and Fig. 12, and the particle size

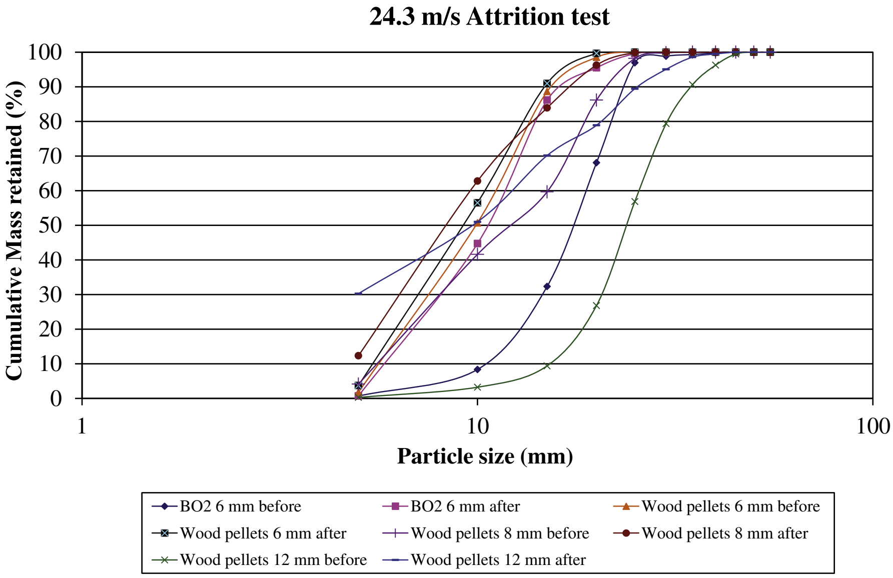

Fig. 14 – Attrition test particle size distribution results (24.3 m/s).

distribution based on the visual results of the attrition test are presented by Fig. 13 and Fig. 14. Results show that torrefied pellets are stronger than most of the wood pellets.

4. Conclusions and recommendations

A series of experiments were carried out in order to study the significant physical material properties of solid biomass fuels, and the results of these tests are summarized in Table 17.

Several important aspects were investigated through these experiments, including physical material properties, and the characteristics when the materials interact with the storage and handling equipment. The test results show that wood pellets have best flow-ability among the test materials, followed by torrefied pellets, and wood chips. The high moisture content of the wood chips is one of the reasons for their behaviors in terms of flow-ability, since the partially composed wood chips are more brittle.

For a large-scale biomass bulk terminal, it is crucial to be able to manage all the cargos flow via the terminal well. In order to deploy or design suitable equipment to handle solid biomass materials properly, it is essential to understand their physical properties. The test materials used represent the feedstock a co-firing power plant uses, and since there is no quantitative guidelines from existing standards, the test results can be used as references in this respect.

However, the connection between these properties and the perspectives of equipment is not done within the scope of this paper. For a better understanding with regard to the equipment, it is crucial to make further interpretations: to compare these solid biomass properties with other bulk materials those have been handled and studied fully (e.g. coal). Based on the comparison, it gives indication whether dedicated equipment for biomass materials is necessary.

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